

2011 RHIC & AGS Annual Users' Meeting



June 20-24, 2011

Jet and Electromagnetic Tomography of High-energy Heavy-ion Collisions



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CCNU & LBNL

Relativistic Heavy-ion Collisions



Two questions we ask:

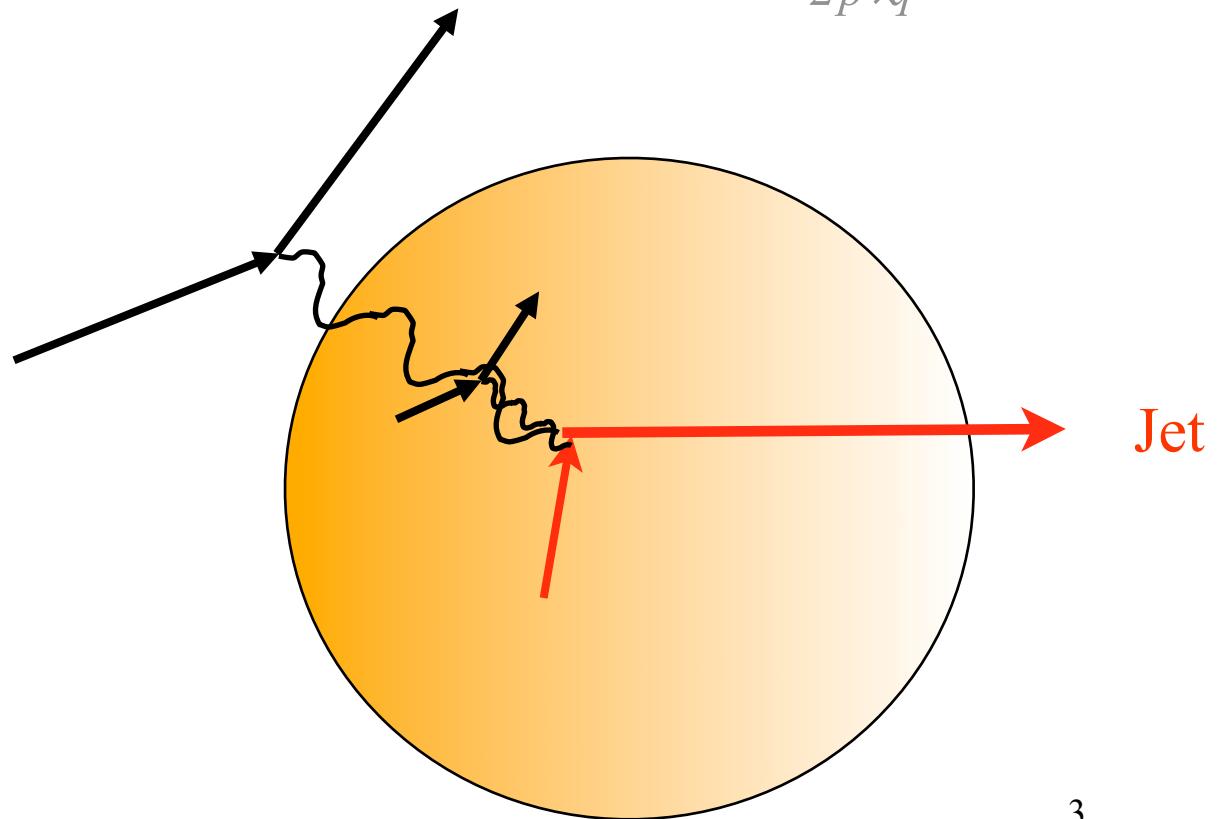
- What is the phase structure of QCD
- What are the properties of nuclear matter in extreme conditions?

Probing Nuclear Matter



$$W_{\mu\nu}(q) = \frac{1}{4\pi} \int d^4x e^{iq\cdot x} \langle A | j_\mu^{em}(0) j_\nu^{em}(x) | A \rangle = -e_T^{\mu\nu} F_1(x_B) + e_L^{\mu\nu} F_2(x_B)$$

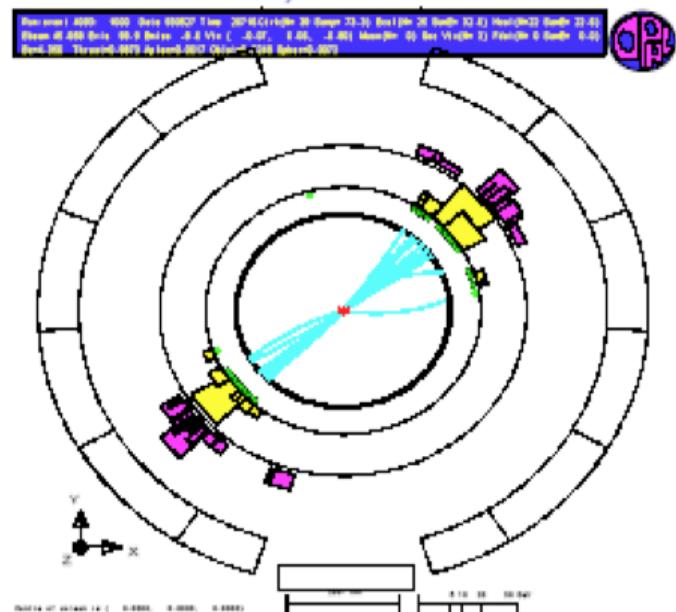
$$x_B = \frac{Q^2}{2 p \cdot q}$$



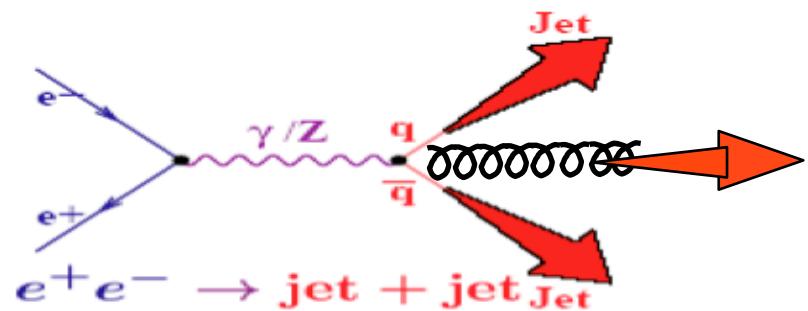
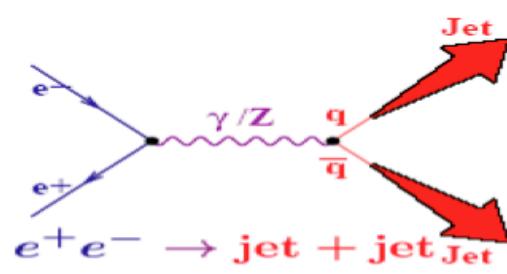
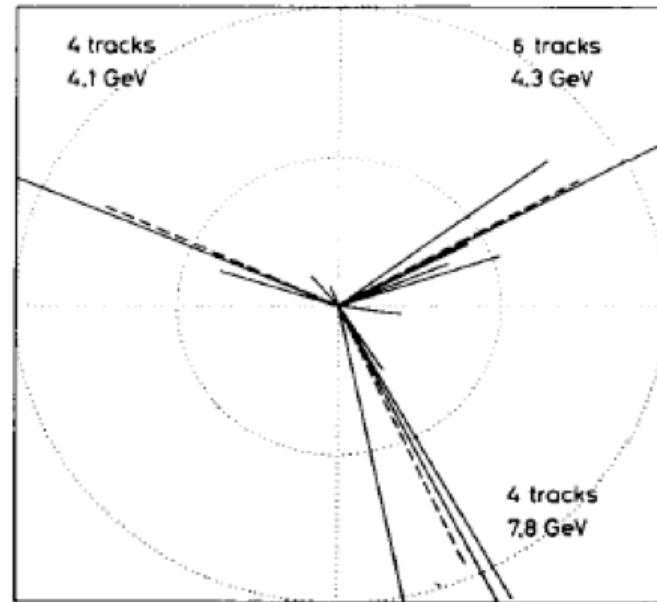
Jet in e^+e^- Annihilation



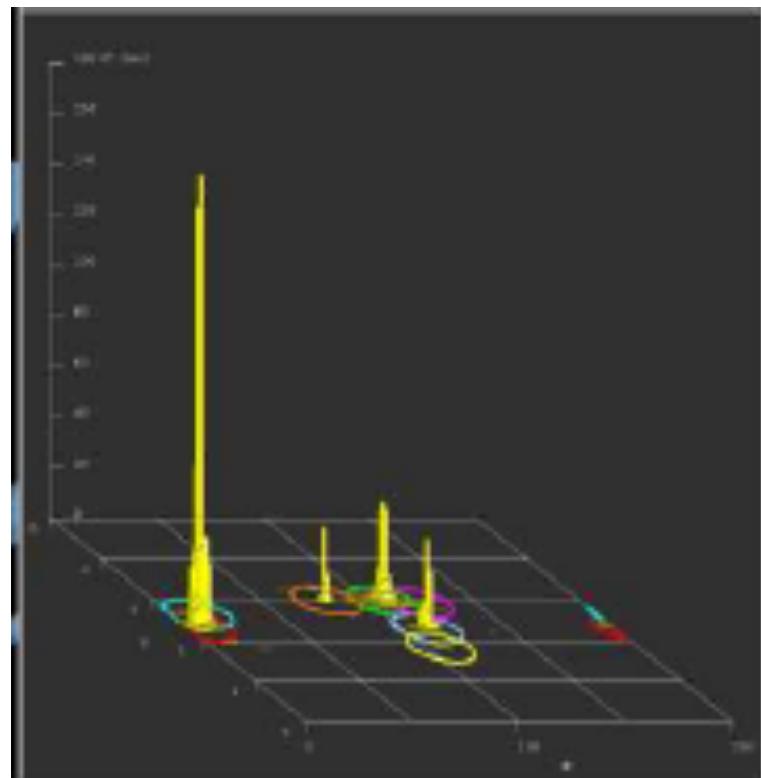
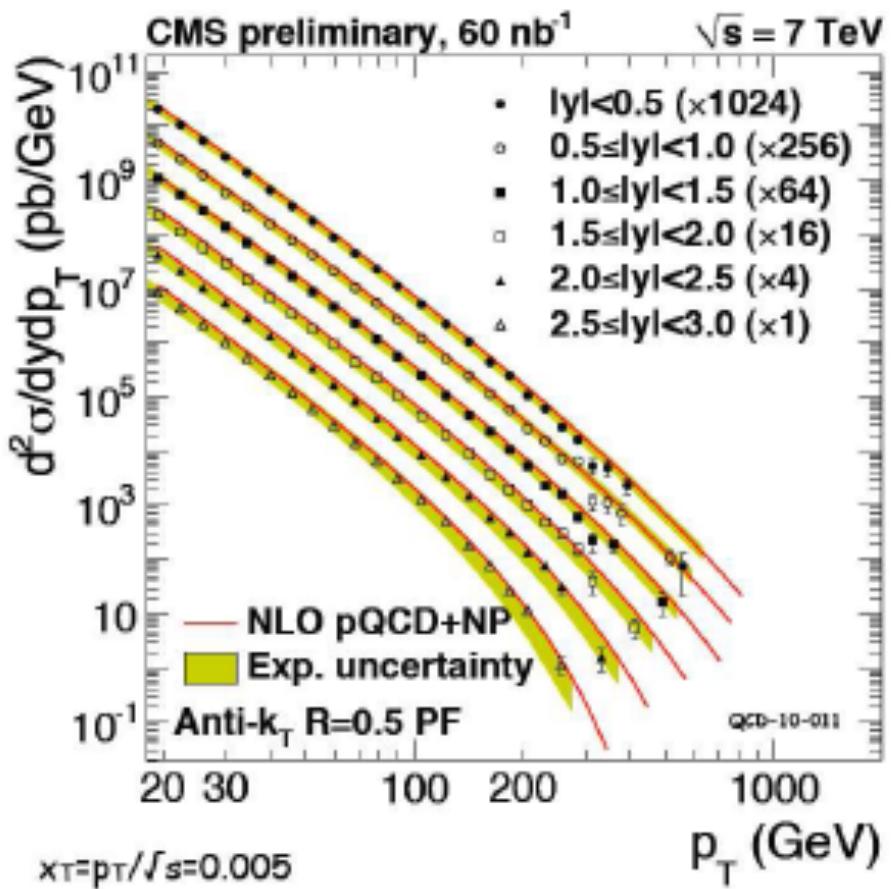
LEP ($\sqrt{s} = 90 - 205$ GeV)



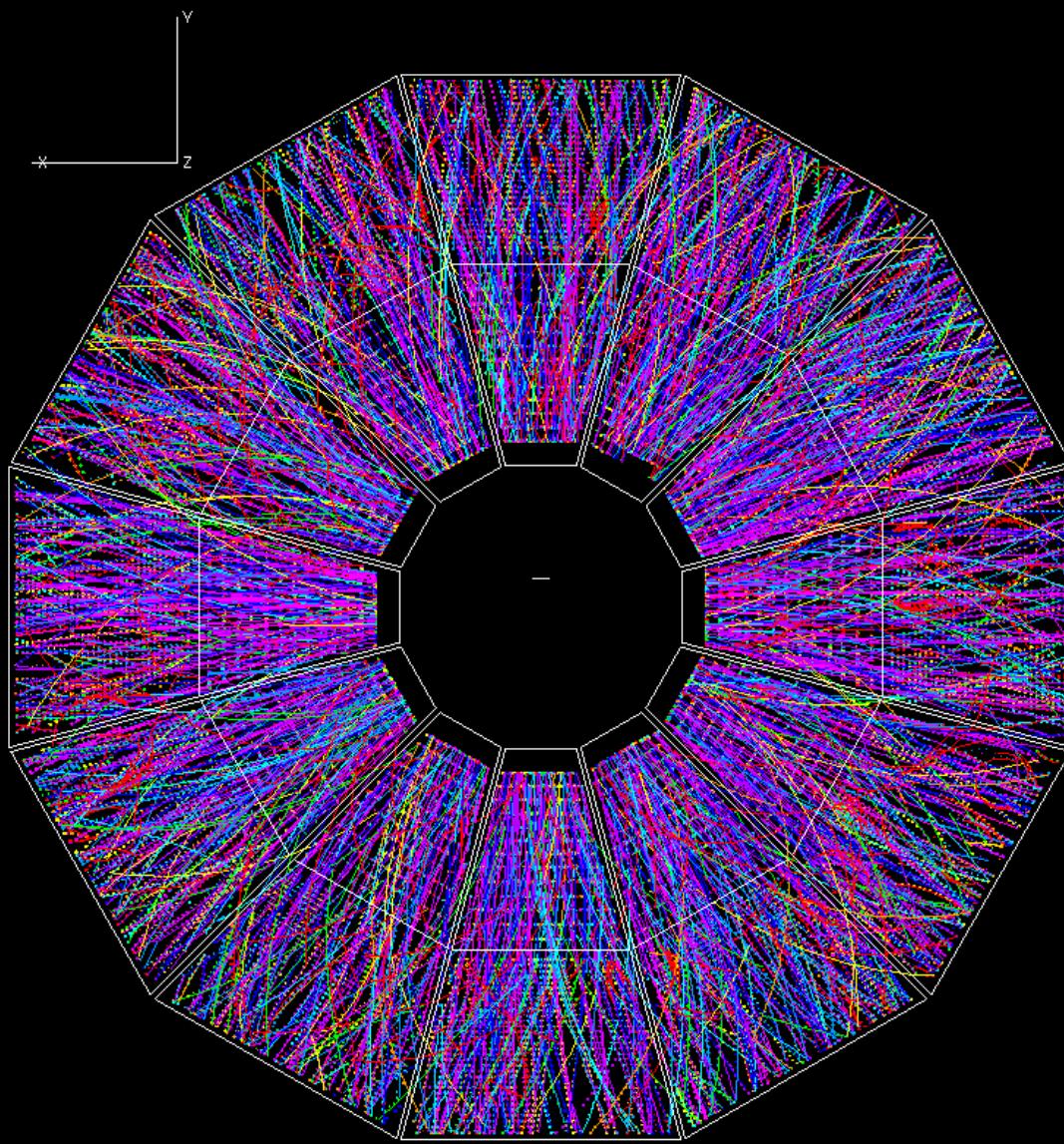
TASSO



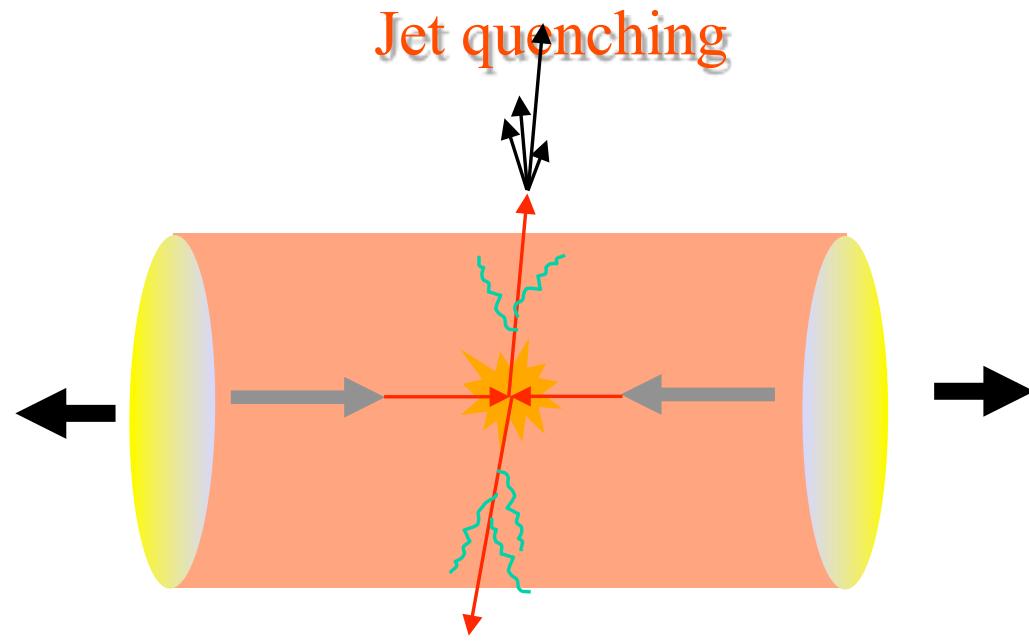
Jets in pp collisions at LHC !!!



Jets at RHIC



Hard Probes of Dense Matter



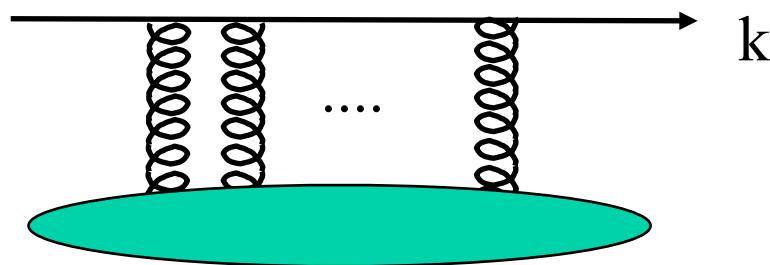
$\Delta D(z, k_\perp)$

k_T broadening

$$\frac{dE}{dx}$$

$$\hat{q}$$

Jet Transport in Medium



Classical Lorentz force: $\frac{d\vec{p}_\perp}{d\tau} = g\vec{F}_{\perp\mu} v^\mu$

$$\vec{W}_\perp(y^-, \vec{y}_\perp) \equiv i\vec{D}_\perp(y) + g \int_{-\infty}^{y^-} d\xi^- \vec{F}_{+\perp}(\xi^-, y_\perp)$$

Jet Transport Operator

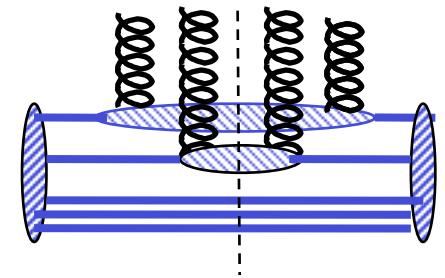
$$f_A^q(x, \vec{k}_\perp) = \int \frac{dy^-}{4\pi} e^{ixp^+ y^-} \langle A | \bar{\psi}(0) \gamma^+ \exp[\vec{W}_\perp(y^-) \cdot \nabla_{k_\perp}] \psi(y^-) | A \rangle \delta^{(2)}(\vec{k}_\perp)$$

Liang, XNW & Zhou (2008)

Momentum Broadening



$$\left\langle \left\langle W_{\perp}^{2n} \right\rangle \right\rangle_A \sim \left[\int dy \frac{\rho_A(y)}{2p^+} \langle N | F_{+\perp} F_{+\perp} | N \rangle \right]^n \sim \left[\int dy \rho_A(y) x G_N(x) \right]^n$$



2-gluon correlation approximation

$$\Delta = \langle \Delta k_{\perp}^2 \rangle = \int d\xi_N^- \hat{q}(\xi_N) \left[-\frac{(\vec{k}_{\perp} - \vec{q}_{\perp})^2}{\Delta} \right] f_N^q(x, \vec{q}_{\perp})$$

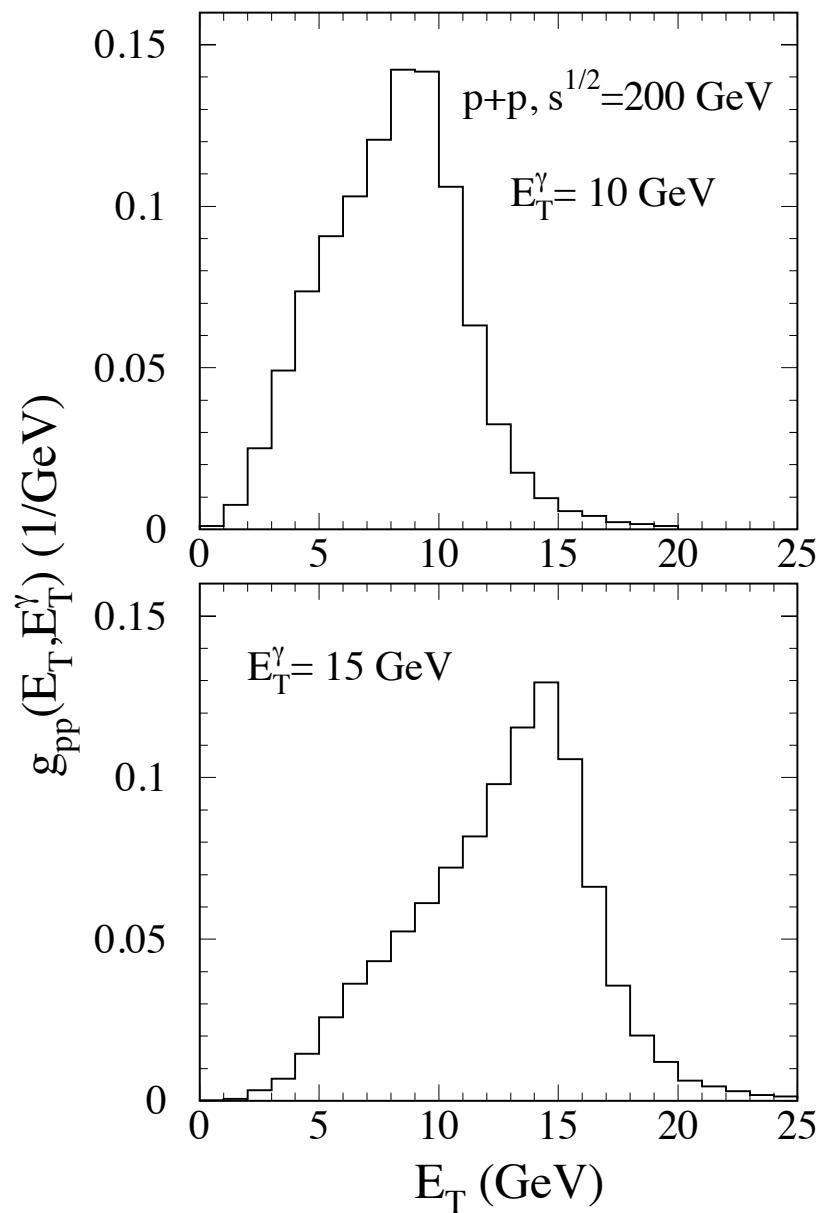
Liang, XNW & Zhou'08
 Majumder & Muller'07
 Kovner & Wiedemann'01
 BDMPS'93

$$f_A^q(x, \vec{k}_{\perp}) \approx \frac{A}{\pi \Delta} \int d^2 q_{\perp} \exp \left[-\frac{(\vec{k}_{\perp} - \vec{q}_{\perp})^2}{\Delta} \right]$$

$$\hat{q}(\xi_N) \equiv \frac{4\pi^2 \alpha_s C_F}{N_c^2 - 1} \rho_A(\xi_N) x G_N(x) \Big|_{x \approx 0}$$

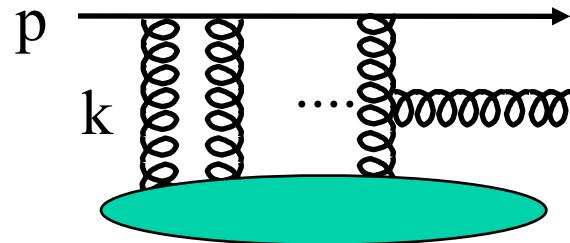
Jet transport parameter

Jet Acoplanarity



$\hat{q} \sim 1-2 \text{ GeV}^2/\text{fm}$

Parton Energy Loss



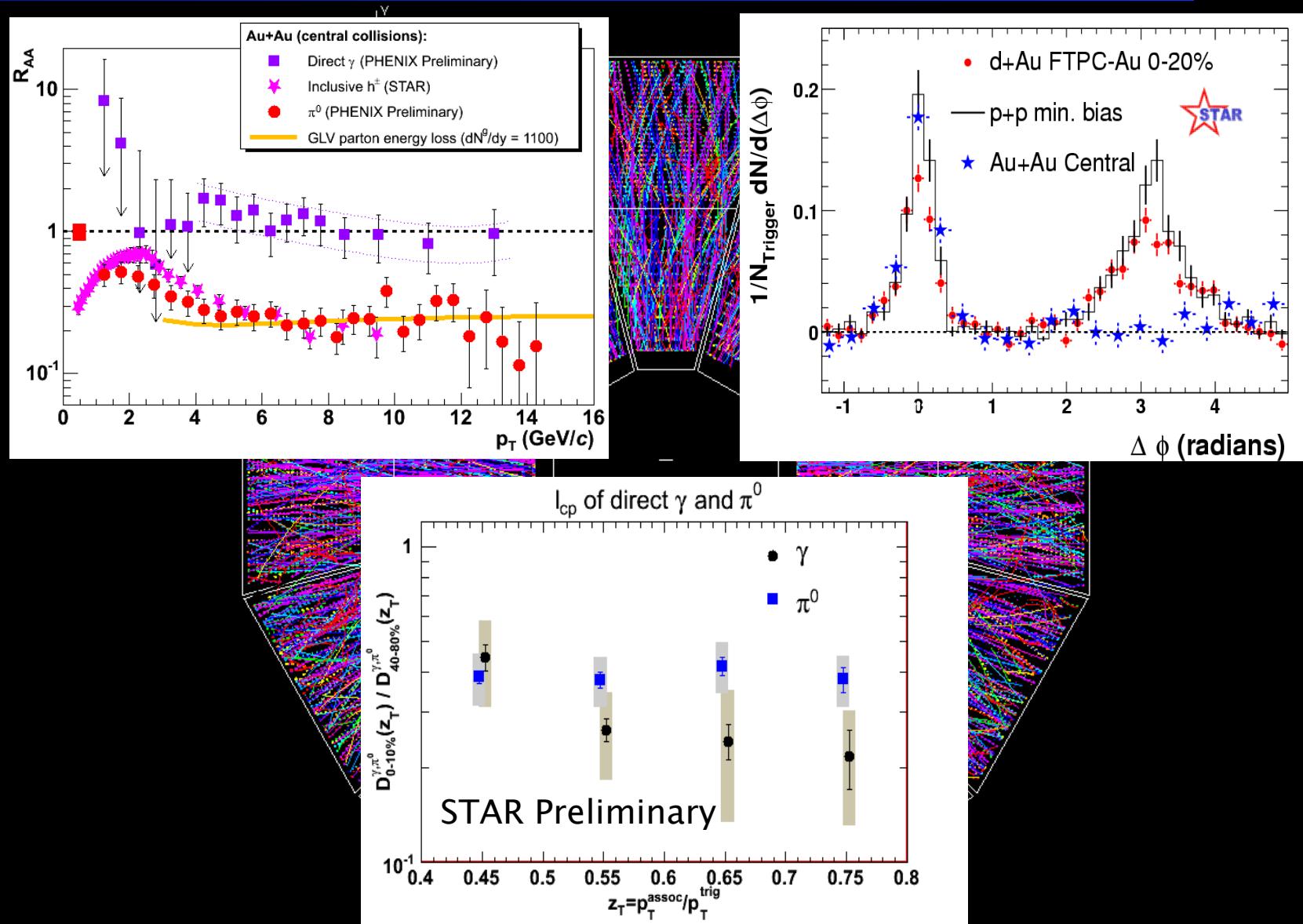
Splitting functions in medium

$$\Delta\gamma(z, \ell_\perp^2) = C_A \frac{1+z^2}{(1-z)_+} \frac{2}{\ell_\perp^4} \int d\xi^- \hat{q}(\xi) [1 - \cos(x_L p^+ \xi^-)]$$

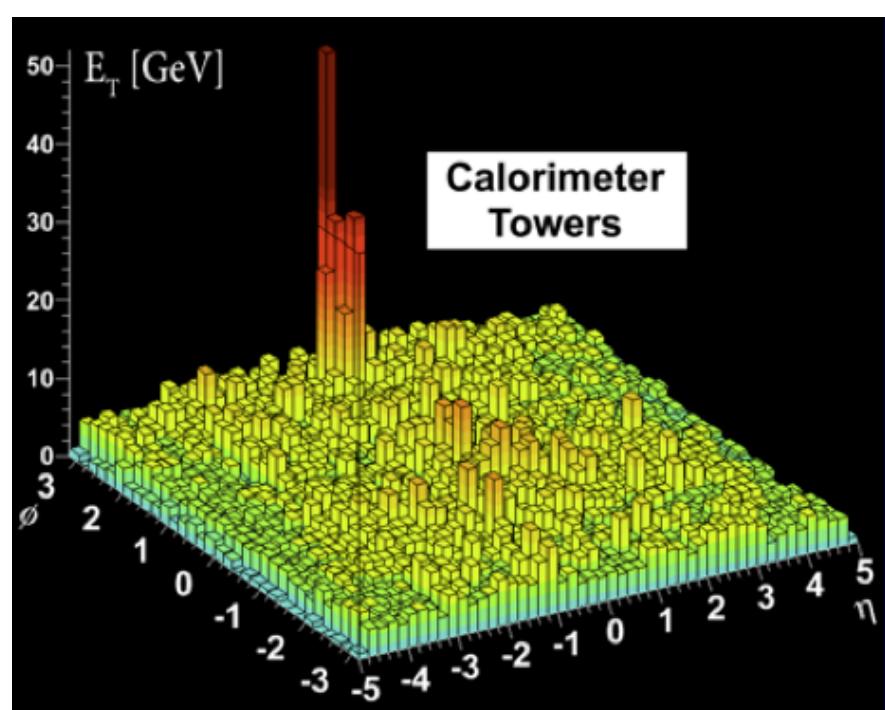
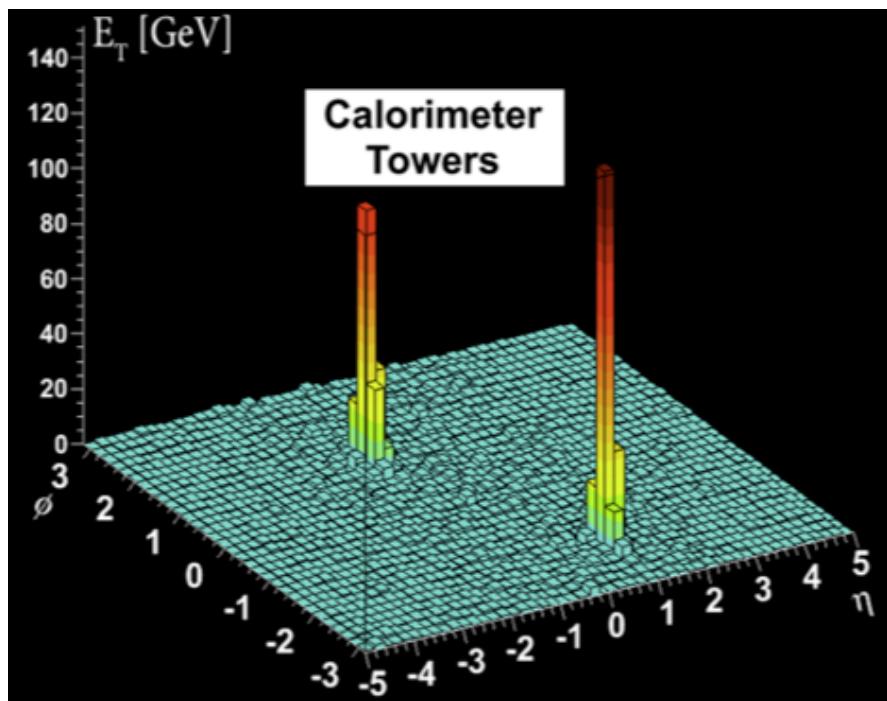
Parton Energy Loss

$$\frac{\Delta E}{E} = C_A \frac{\alpha_s}{2\pi} \int \frac{dl_T^2}{l_T^4} \int dz [1 + (1-z)^2] \int d\xi^- \hat{q}(\xi) 4 \sin^2(x_L p^+ \xi^- / 2)$$

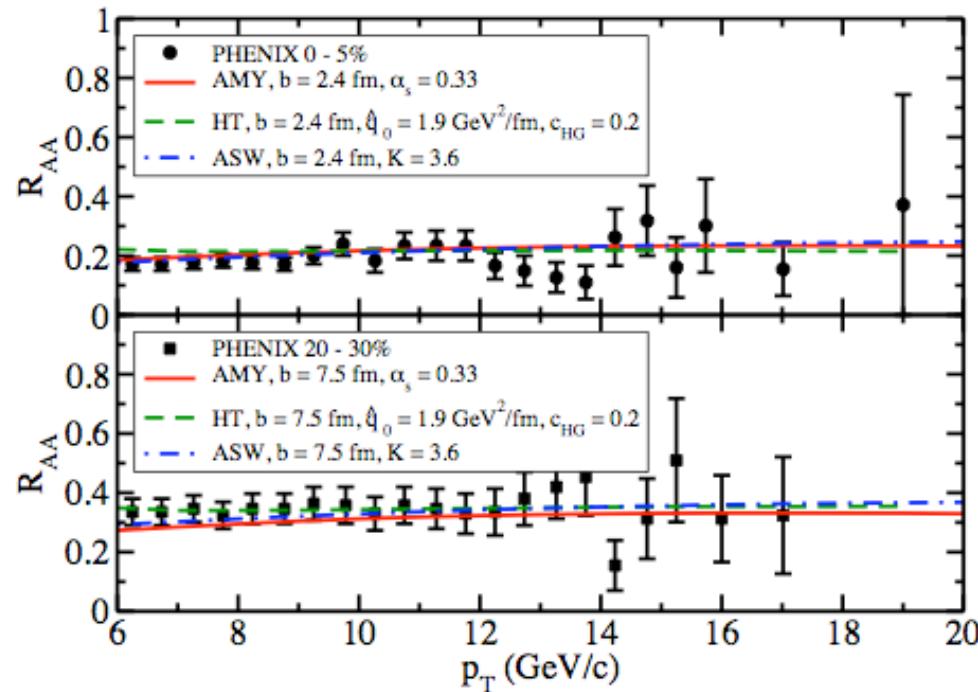
Jet Quenching phenomena at RHIC



Jet Quenching at LHC



Jet quenching phenomenology



Bass et al, 2008

$\hat{q}(\vec{r}, \tau)$	ASW	HT	AMY
scales as	\hat{q}_0	\hat{q}_0	\hat{q}_0
$T(\vec{r}, \tau)$	$10 \text{ GeV}^2/\text{fm}$	$2.3 \text{ GeV}^2/\text{fm}$	$4.1 \text{ GeV}^2/\text{fm}$
$\epsilon^{3/4}(\vec{r}, \tau)$	$18.5 \text{ GeV}^2/\text{fm}$	$4.5 \text{ GeV}^2/\text{fm}$	
$s(\vec{r}, \tau)$		$4.3 \text{ GeV}^2/\text{fm}$	

Jet & Electromagnetic Tomography



- Go beyond soft and collinear approximation
 - parton recombination, heavy quark
- Realistic space-time evolution of bulk matter
 - viscous hydro, parton and hadron cascade
- Develop new and powerful Monte Carlo
 - include interaction of jet and dynamic medium
- Systematic phenomenological studies
 - quantitative tomography of dynamic medium

Approaches to parton energy loss



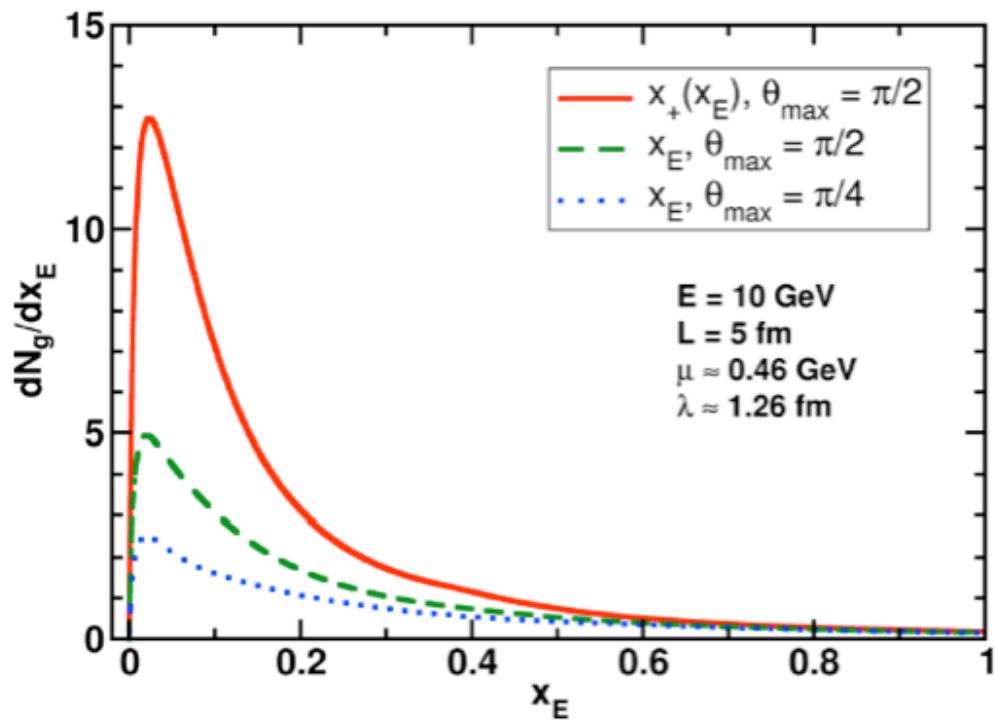
- **Armesto, Salgado, Wiedemann (ASW)**
 - Static scattering center medium with Yukawa like potentials Path integral over multiple scatterings in the medium
- **Gyulassy, Levai, Vitev (GLV/DGLV/ WHDG)**
 - Medium of heavy (static) scattering centers with Yukawa like potentials Calculate order by order in number of scatterings per emission
- **Arnold, Moore, Yaffe (AMY)**
 - Thermalized partonic medium at $T \rightarrow \infty, g \rightarrow 0$, HTL plasma
Multiple scattering resummation on near on-shell parton
- **Higher Twist (HT)**
 - Arbitrary medium, no model (soft scattering assumed) An expansion in $1/Q^2$ of multiple scattering on a hard parton

A Brick Problem



Systematic comparisons of different approaches:

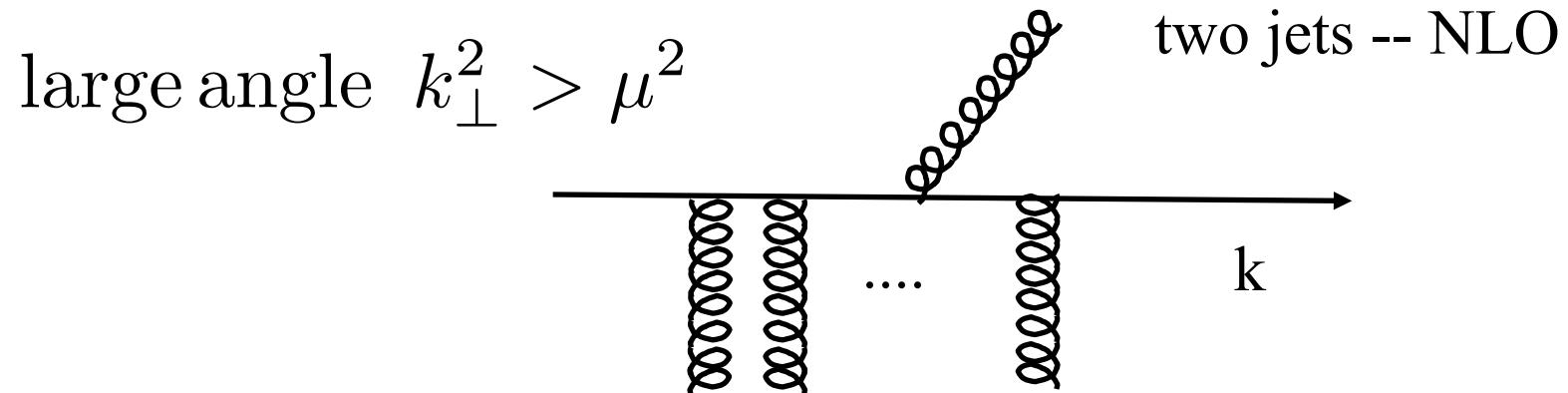
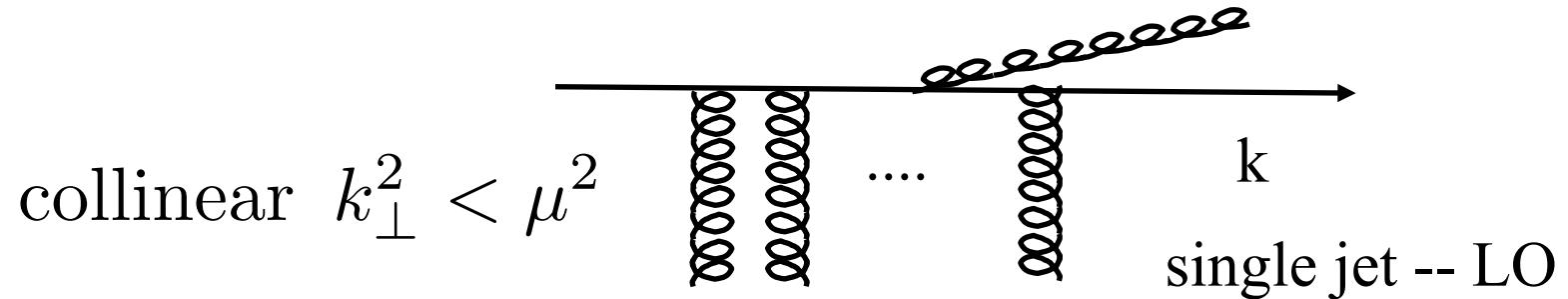
N. Armesto et al. arXiv:1106.1106



Single gluon emission

Sensitivity to maximum angle cut-off for gluon emission

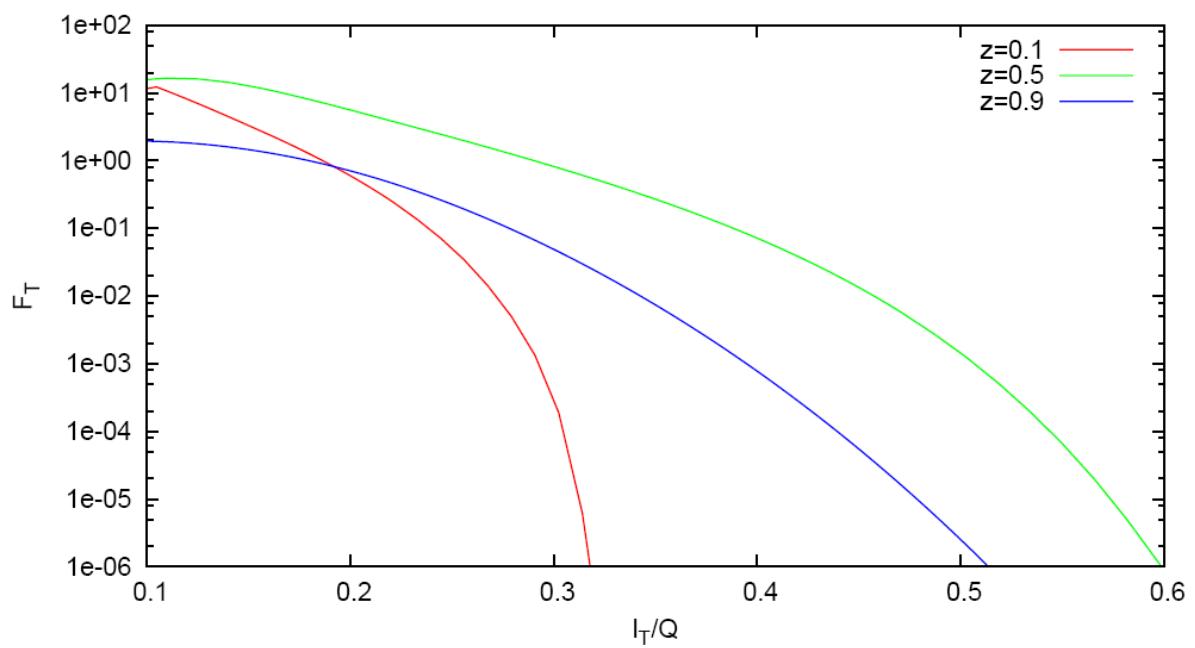
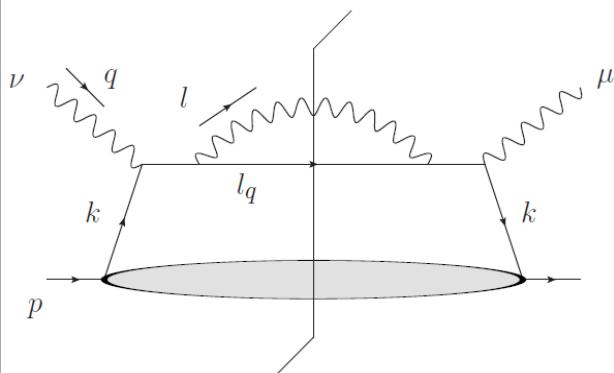
Collinear approximation & NLO pQCD



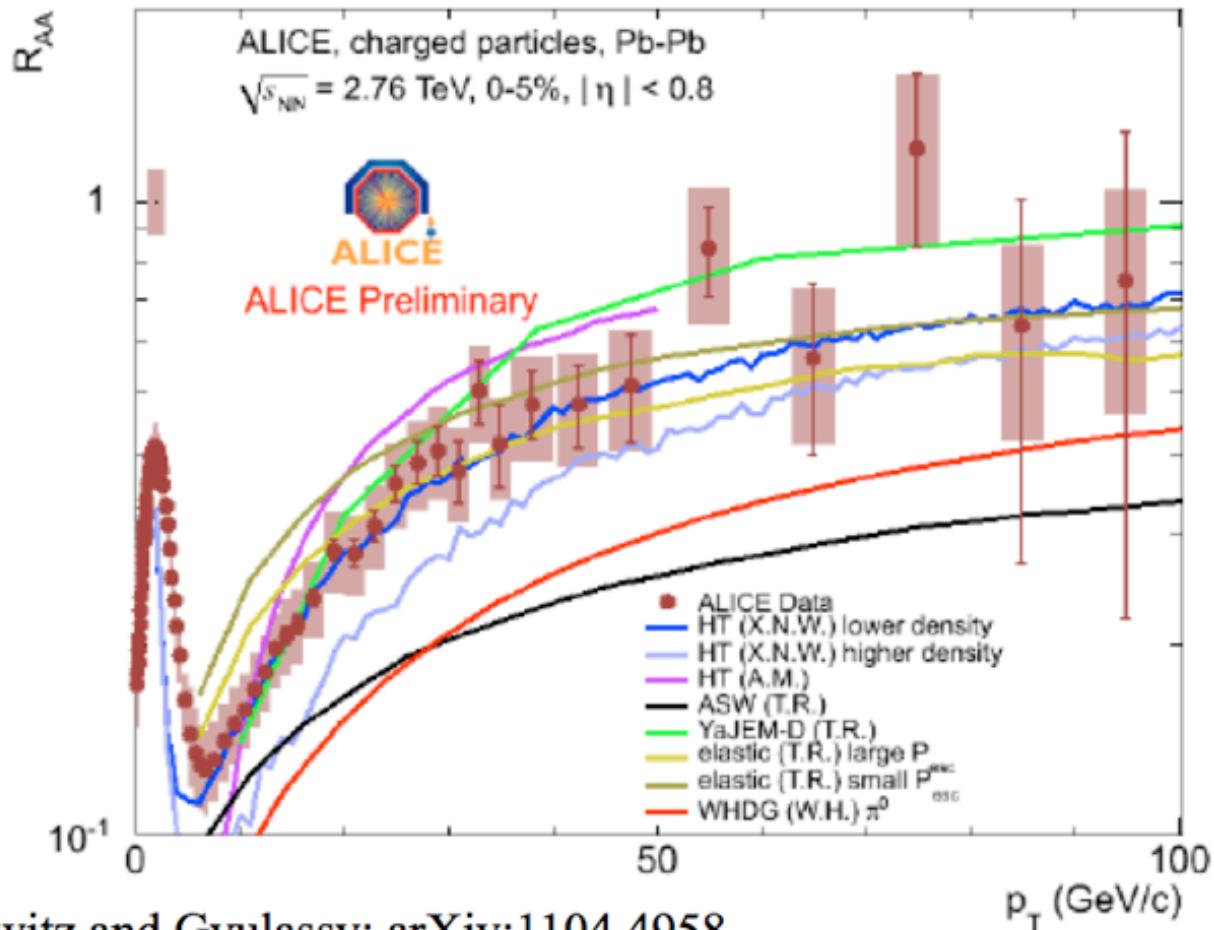
Example: LT photon radiation



$$\begin{aligned}
 F_T(z, x_B, y, \vec{l}_T) = & \frac{4A(1-z)Q^2}{(2\pi)^3 \pi x_B \Delta_{2F}} \int e^{-k_T^2/\Delta_{2F}} f_{q/N}(x) \Big|_{x=x_B \left[1 + \frac{(zk_T + l_T)^2}{z(1-z)Q^2} \right]} \times \\
 & \left\{ \frac{1 + (1-z)^2}{(zk_T + l_T)^2} - \frac{(zk_T + l_T)^2}{[z(1-z)Q^2 + (zk_T + l_T)^2]^2} \right. \\
 & \left. + \frac{2(1-z)}{[z(1-z)Q^2 + (zk_T + l_T)^2]} - \frac{6z^2(1-z)^2Q^2}{[z(1-z)Q^2 + (zk_T + l_T)^2]^2} \right\} d^2 k_T,
 \end{aligned}$$



Survival under the LHC sea

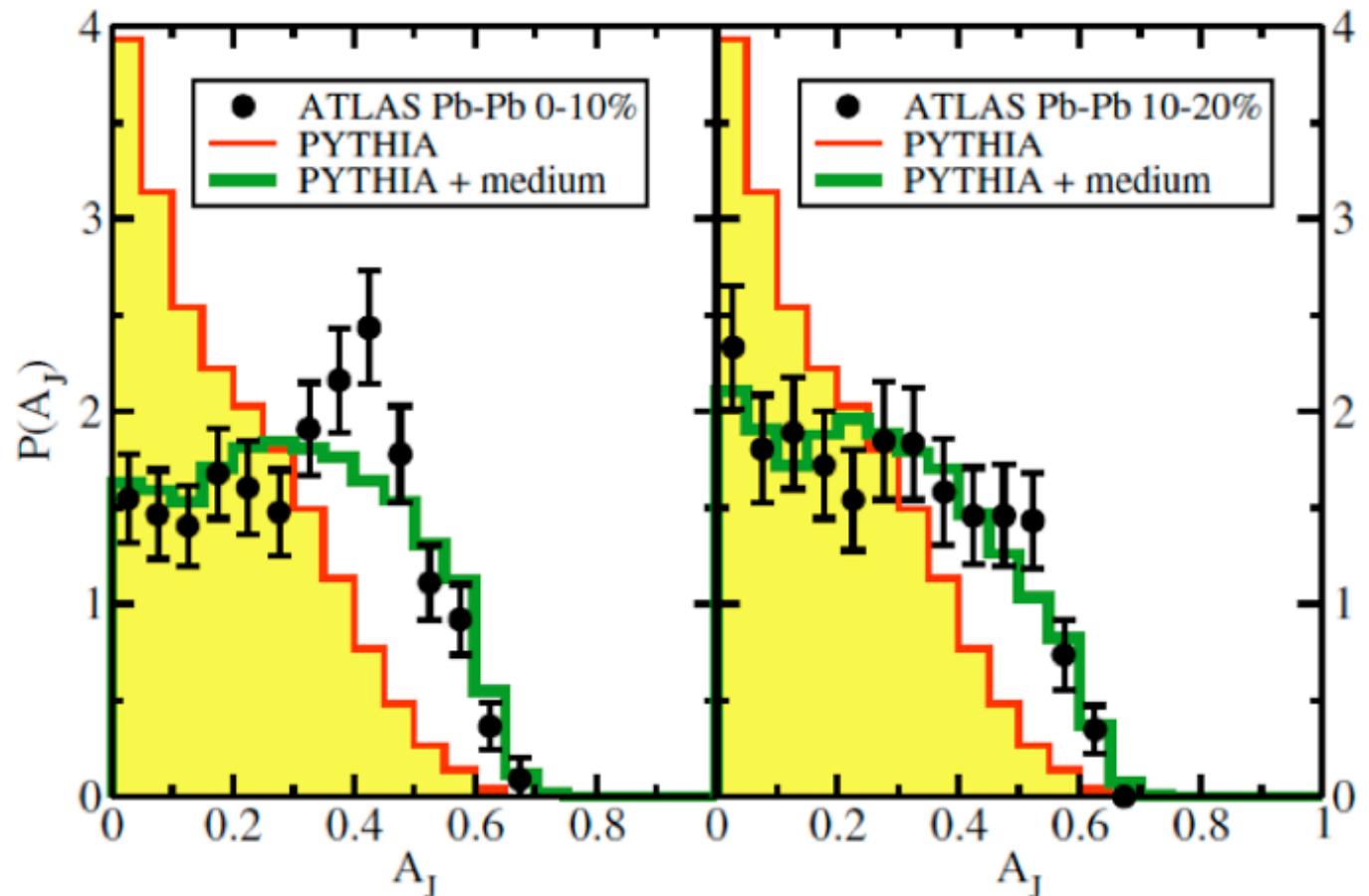


Horowitz and Gyulassy: [arXiv:1104.4958](https://arxiv.org/abs/1104.4958)

Majumder and Shen: [arXiv:1103.0809](https://arxiv.org/abs/1103.0809)

Chen et. al. [arXiv:1102.5614](https://arxiv.org/abs/1102.5614)

Di-Jet Asymmetry

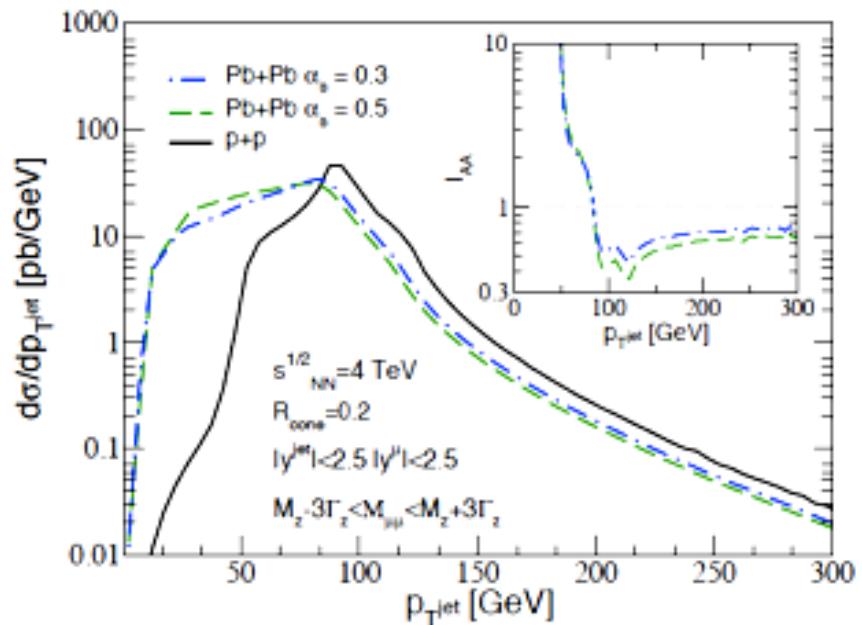
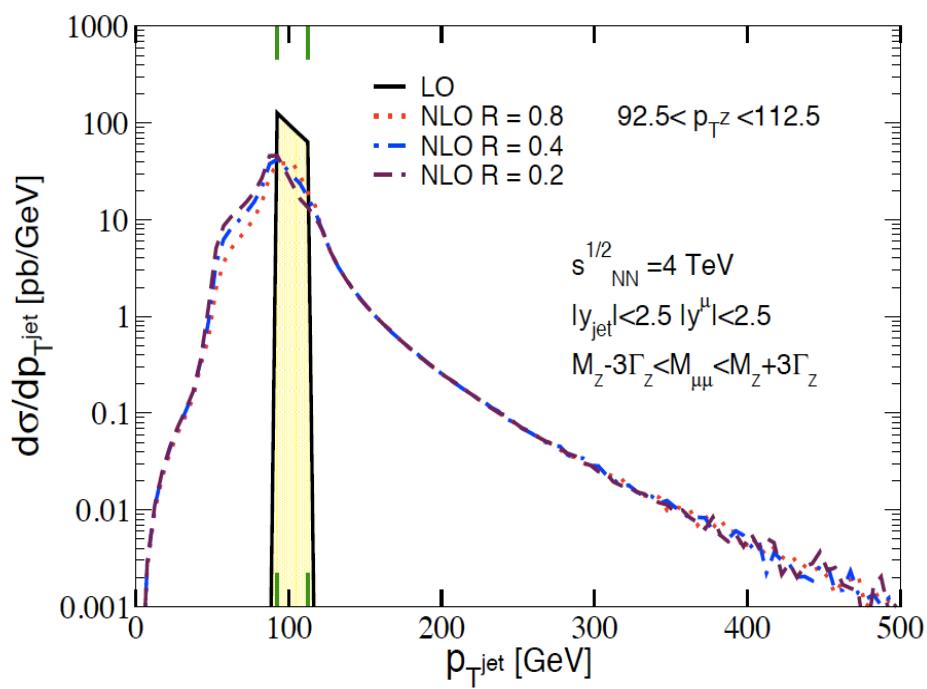


Jet transport
with HT
kernel

Qin and Muller Phys.Rev.Lett.106:162302,2011

B. Schenke, C. Gale, S. Jeon, Phys.Rev.C80:054913 (2009)

Z0 tagged jet



R.B. Neufeld et al., (2010)

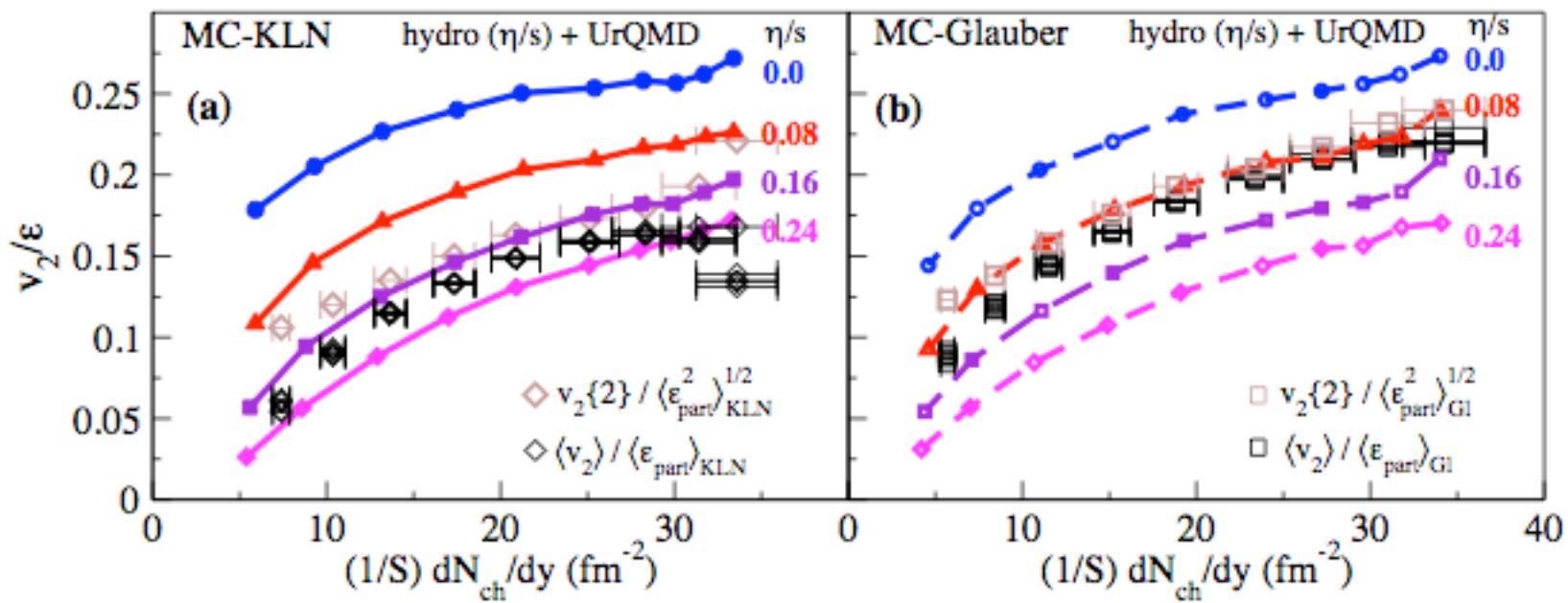
Bulk Evolution



jet-medium interaction in a dynamic medium

developed 3+1D viscous hydro

developed hydro/hadron cascade interface

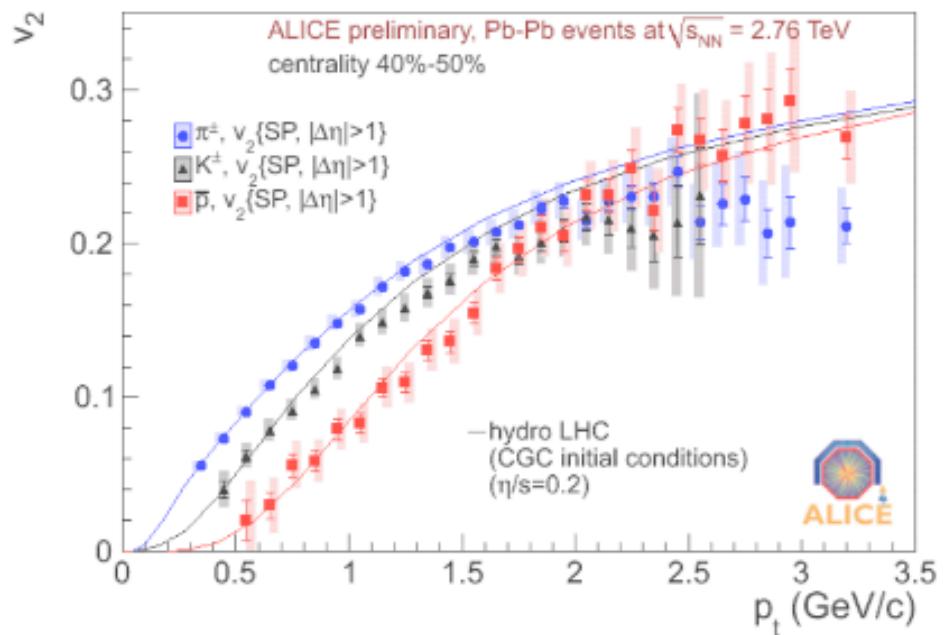
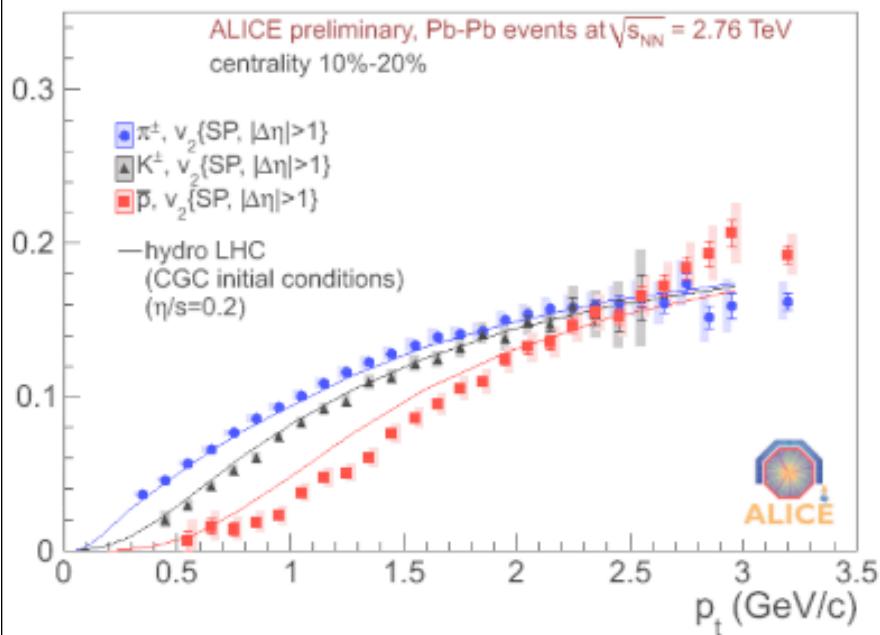


Flow at LHC

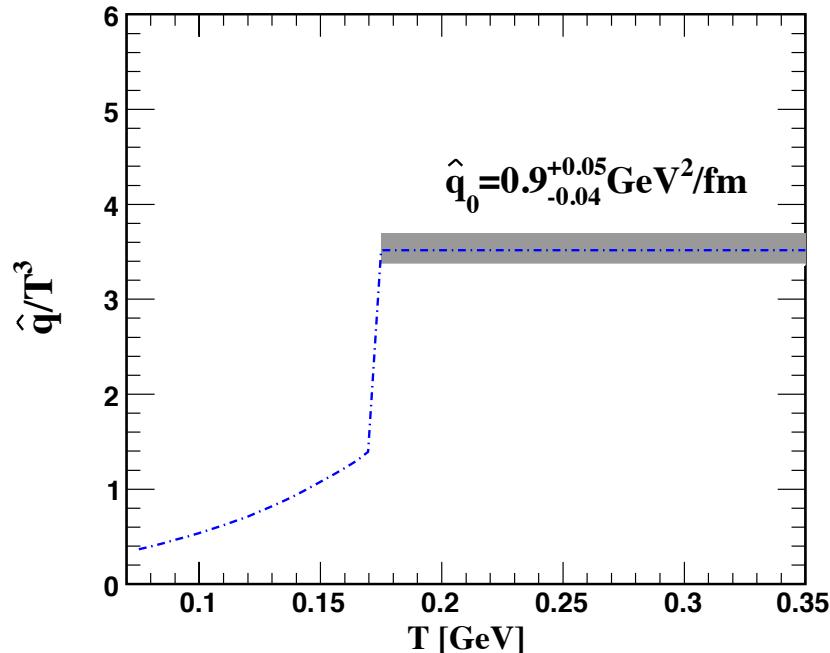


Data: ALICE

Lines: Shen et al., arXiv:1105.3226 (VISH2+1)



Jet quenching in hadronic phase



30% quenching from
hadronic phase

Chen, Greiner, Wang, XNW, Xu
(2010)

$$\hat{q}(\tau, r) = \hat{q}_0 \frac{\rho^{QGP}(\tau, r)}{\rho^{QGP}(\tau_0, 0)} (1 - f) + \hat{q}_h(\tau, r) f$$

$$\hat{q}_h = \frac{\hat{q}_N}{\rho_N} \left[\frac{2}{3} \sum_M \rho_M(T) + \sum_B \rho_B(T) \right]$$

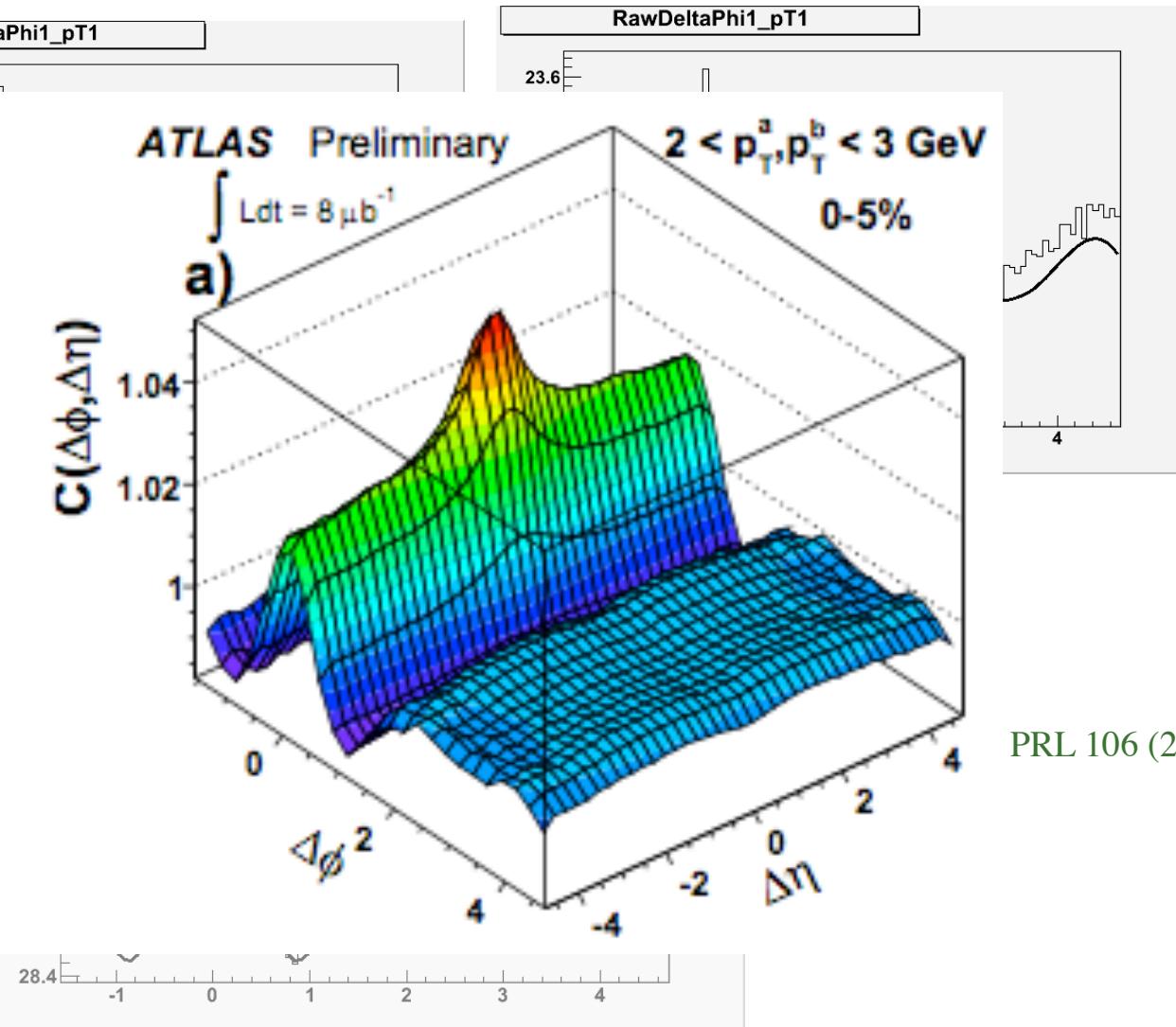
$$\hat{q}_N = 0.02 \text{ GeV}^2/\text{fm}$$

from HERA DIS

Jet-induced medium excitation



$3 < \Delta\eta < 4$
 $\Delta\eta < 1$



Goals of JET Collaboration



- Extend and improve the current framework for the study of jet-medium interaction
- Develop Monte Carlo program for jet quenching
- Coupling to realistic bulk evolution
- Systematic phenomenological study of jet quenching

JET Publications



Slides and Documents from 2010 Collaboration meeting – jetmemberwiki

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2

days since

JET Summer School and
Collaboration meeting

Publications

(Publications are ordered chronologically according to the arXiv number)

- 38) A. Buzzatti and M. Gyulassy,
Jet Flavor Tomography of Quark Gluon Plasmas at RHIC and LHC,
[arXiv:1106.3061](#).
- 37) Chun Shen, U. Heinz, P. Huovinen, and H. Song,
Radial and elliptic flow in Pb+Pb collisions at the Large Hadron Collider from viscous hydrodynamics,
Phys. Rev. C, submitted [[arXiv:1105.3226](#)].
- 36) W. A. Horowitz and M. Gyulassy,
The Surprising Transparency of the sQGP at LHC,
[arXiv:1104.4958](#).
- 35) Z. Qiu and U. Heinz,
Event-by-event shape and flow fluctuations of relativistic heavy-ion collision fireballs,
Phys. Rev. C, submitted [[arXiv:1104.0650](#)].
- 34) Min He, Rainer J. Fries and Ralf Rapp,
Thermal Relaxation of Charm in Hadronic Matter,
Phys. Lett. B submitted [[arXiv:1103.6279](#)].
- 33) T. Song, K. Han, and C. M. Ko,
Charmonium Production in Heavy-Ion Collisions from SPS to LHC,
Phys. Rev. C, submitted [[arXiv:1103.6197](#)].
- 32) J. Xu and C. M. Ko,
Triangular Flow in Relativistic Heavy Ion Collision,
Phys. Rev. C, submitted [[arXiv:1103.5187](#)].

JET Annual Summer Schools



June 14-17, 2010, LBNL

June 15-17, 2011, Duke



For the next fives

